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ORIGINAL ARTICLE

First geophysical and shallow ice core investigation of the Kazbek plateau glacier, Caucasus Mountains

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Abstract First-ever ice core drilling at Mt. Kazbek (Caucasus Mountains) took place in the summer of 2014. A shallow ice core (18 m) was extracted from a plateau at ~4500 m a.s.l. in the vicinity of the Mt. Kazbek summit (5033 m a.s.l.). A detailed radar survey showed that the maximum ice thickness at this location is ~250 m. Borehole temperature of −7 °C was measured at 10 m depth. The ice core was analyzed for oxygen and deuterium isotopes and dust concentration. From the observed seasonal cycle, it was determined that the ice core covers the time interval of 2009–2014, with a mean annual snow accumulation rate of 1800 mm w. eq. Multiple melt layers have been detected. $\delta^{18}O$ values vary from −25 to −5‰. The dust content was determined using a particle sizing and counting analyzer. The dust layers were investigated using scanning electron microscopy and X-ray diffraction analysis. Dust can be separated into two categories by its origin: local and distant. Samples reflecting predominantly local origin consisted mainly of magmatic rocks, while clay minerals were a characteristic of dust carried over large distances, from the deserts of the Middle East and Sahara. The calculated average dust flux over three years at Kazbek was of 1.3 mg/cm^2 a^{-1}. Neither $\delta^{18}O$ nor dust records appear to have been affected by summer melting. Overall, the conditions on Kazbek plateau and the available data suggest that the area offers good prospects of future deep drilling in order to obtain a unique environmental record.

Keywords Mountain glaciers · Ice cores · The Caucasus · Mt. Kazbek · GPR · Oxygen isotopes · Dust content

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Introduction

Some of the most informative sources of paleoclimatic information are the ice core archives, both polar and high altitude. However, in the very near future, many of them are in danger of vanishing completely due to continued warming (Zemp et al. 2015). Because of increasing melting in the temperate and tropical latitudes, some mountain glaciers at these latitudes will disappear. At the same time, the feeding zones of the remaining glaciers will become homogenized due to the infiltration of melt water, thus

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making the ice unsuitable for paleoenvironmental research. Therefore, efforts to recover those records are urgently needed (Zhang et al. 2015).

In Russia, ice cores suitable for paleoclimatic analysis can be recovered only from a few glaciers. The glaciers of the Caucasus Mountains have the highest prospects, as evidenced by the study of the first Elbrus deep ice core, obtained in 2009 (Mikhalenko et al. 2015). However, this unique archive is threatened by the warming, which in the coming years may eliminate the climatic signal due to the penetration of melt water into the interior of the glacier.

The two regions of the world where most ice coring was done are Greenland and Antarctica, from where valuable multiparameter records are available (Petit et al. 1999; EPICA Community Members 2006; Jouzel 2013). Considering Eurasia, the most populated continent, deep ice cores have been recovered from the following mid-latitude mountain ranges: the Alps (e.g., Wagenbach and Geis 1989; Mariani et al. 2014), the Himalaya (e.g., Thompson et al. 2000; Davis et al. 2005; Kaspari et al. 2007), the Tibet (e.g., Thompson et al. 1997; Kang et al. 2007), Tien Shan (e.g., Wu et al. 2010, 2015), the Altai (e.g., Aizen et al. 2006; Eichler et al. 2012, 2014), Kamchatka (Matoba et al. 2014) and the Caucasus (Mikhalenko et al. 2015).

In Europe, long records are available only in the Alps and in the high mountains of the Caucasus (the latter are sometimes attributed to Asia). During the past decades there have been several dozen of ice cores drilled in the Alps. The studies performed on those cores allowed the establishment of trends in temperature, precipitation, dust and various pollutants over the past several centuries. The most well known of these studies have been performed on four glaciers: the Colle Gnifetti saddle, 4455 m a.s.l. (Wagenbach et al. 1988; Doscher et al. 1995), Col du Dôme in the Monblan mountain massif, 4250 m (Preunkert et al. 2000, 2001; Legrand et al. 2013), Grenzgletscher, Monte Rosa massif, 4200 m (Eichler et al. 2000, 2001), and Fiescherhorn, 3900 m (Schotterer et al. 1997, 2002; Schwikowski et al. 1999; Jenk et al. 2006). There have been several cores drilled on each of these glaciers. It is widely recognized that the ice core studies in the Alps made a significant contribution to understanding climatic and atmospheric processes.

The Caucasus, where multiple archives of paleogeographic information are concentrated, is suitable for creating comprehensive paleoclimatic reconstructions. Past research (Solomina et al. 2013, 2014; Mikhalenko et al. 2015) reveals that trends in the Caucasus climatic variability can be extended to the surrounding areas of southern European Russia. In this respect, the Northern Caucasus can be regarded as a key area for large-scale generalizations. Despite many years of efforts researchers (Serebryany et al. 1984; Khokhlova et al. 2007), the task of reconstructing the climate and environment in the Caucasus during the past millennia is far from being accomplished (Solomina et al. 2014). In contrast to the Alps, the potential of the Caucasus Mountains for ice core studies has not been realized yet. The only deep drilling was performed on Mt. Elbrus, where an ice core recovered at 5115 m a.s.l. provides a 182-m record ($\sim$350–400 years) (Mikhalenko et al. 2015). It should be noted that drilling at the point of the maximum thickness of the glacier would yield a high-resolution record spanning over 600 years (Mikhalenko et al. 2015).

Clearly, more Caucasus ice cores are needed to validate the paleoenvironmental signal observed in the Elbrus ice core (Mikhalenko et al. 2015; Kutuzov et al. 2017). The goal should be making more extensive sets of measurements and extending the duration of the paleorecord. One important objective of the Caucasus research is transfer of pollutants, which in the case of the Alps shows a recent decrease. Glaciers on Caucasus high mountains could serve as recorders of natural and anthropogenic changes occurring in geographical areas whose changes are not reflected in the Alps (e.g., the Middle East) (Shahgedanova et al. 2013; Kutuzov et al. 2013, 2014).

In the large-scale geographical view, the Caucasus Mountains provide another region in Eurasia for examining past environmental variability using high-mountain ice cores, adding to research conducted in the Alps, the Pamirs, the Tien Shan, the Altai, Tibet, and the Himalayas. Altogether, these records would provide a hemispheric view of atmospheric and climatic variability at high resolution and will contribute to understanding global climate change. The ice cores from the Caucasus Mountains, bordering Europe and Asia, will serve as an important component in the continent-scale transect of available high-altitude ice cores in Eurasia. The joint analysis of the data from Eurasian ice cores, with the critical area of the Caucasus that is perfectly located to capture dust and pollutant transfer from the Middle Eastern region, will enable the tracking of changes in natural and anthropogenic emissions. The future Kazbek deep ice core will complement and allow verification of data previously obtained as a result of deep drilling on Mt. Elbrusa in 2009. Determination of the impact of local and large-scale factors on the Caucasus glaciers will become possible.

The glacierized massif of the Kazbek volcano (5033 m a.s.l.) in the Caucasus is well known for a range of natural hazards, particularly glacier hazards. Several catastrophes associated with volcanic activity and surging behavior of Kolka and Devdoraki glaciers have occurred for a number of times (Kotlyakov et al. 2002; Huggel et al. 2005; Evans et al. 2009). The first meteorological observations at the Mt. Kazbek summit were performed in 1911 by M.

Preobrazhenskaya. Subsequently, in 1925, a meteorological station was installed there.

One glaciological study that was performed in the 1960s should be mentioned (Davitaya 1969). In that study, the first attempt was made to construct a time profile of chemicals using samples from the glacier crevasse. No comprehensive glaciological studies have been performed on Mt. Kazbek in the past decades. Glaciological work is needed here not only from the point of view of paleoenvironmental records but also to predict the effects of possible strong volcanic activity leading to rapid melting. The Kazbek deep ice core would nicely complement the Elbrus ice core allowing separating local and large-scale influences in dust supply, transfer of pollutants, etc

The main objective of this work was (1) to investigate various characteristics of the Kazbek plateau glacier from the point of view of future deep drilling, and (2) use the first Kazbek shallow ice core to determine whether annual layers are detectable in the isotopes, to evaluate the dust flux, to use scanning electron microscope and X-ray diffraction analyses to distinguish between local and distant dust sources, and to deduce the age of the ice at the bedrock.

Study site and methods

Ice core drilling site

Mt. Kazbek (42°41′57″ N, 44°31′6″E) is the sixth highest summit in the Caucasus (Fig. 1). It belongs to the Main Caucasus Range. To the west of Kazbek are Mt. Maili (4598 m) and Mt. Djhimara (4780 m). Together, they form the so-called Kazbek–Djhimara mountain massif. Kazbek is a dormant volcano which has a principle two-headed cone and several side cones. The main cone erupted about 185,000 ± 30,000 years ago, while the side cone of New Tkarsheti erupted about 6 thousand years ago (Chernyshev et al. 2002). Valley type glaciers Maili, Kolka (Russia), Suatisi, Mna, Gergeti, Abano, Chachi, Devdoraki (Georgia) are generated at the slopes of Mt. Kazbek.

The flat accumulation zone of the Maili, Devdoraki and Gergeti glaciers is located at the upper part of the Kazbek volcano in the vicinity of the summit at elevations between 4300 and 4500 m. This area will be hereafter referred to as the “Kazbek plateau.” The approximate surface area of the Kazbek plateau is 0.7 km^2. Here, shallow ice cores were recovered in 2014 and 2015 at an elevation of ~4500 m. The drilling site is located on the Kazbek plateau near the summit of Mt. Kazbek (5033 m a.s.l.). Equipment delivery from the base camp was accomplished using a helicopter. 18- and 9-m-long cores were obtained in 2014 and 2015, and three snow pits were excavated at different altitudes from 4500 to 5033 in 2015. Ice cores and snow pits were sampled using pre-cleaned vials. From the moment of collection, snow and ice samples were maintained frozen during transportation and storage.

Climate setting

General atmospheric circulation patterns are common for the Central Caucasus which define an area between Mt. Elbrus and Mt. Kazbek. The area is influenced by a western extension of the Siberian High in winter and by its position between high pressure in the subtropics to the west and the Asian Low in the east (Volodicheva 2002). The values of the mean annual temperature at four Central Caucasus meteorological stations are listed in Table 1 (location of these stations is shown in Fig. 1).

The seasonal changes in the directly measured temperature and precipitation are shown in Fig. 2 (the data cover time interval 1965–1991). Using the moist adiabatic lapse rate of 0.6 °C, the seasonal temperature trend can be estimated for the Kazbek plateau. Mean annual air temperature at Kazbek plateau is −11.6 °C. The months January–February show the lowest calculated air temperature. The average monthly temperature values for the first months of the year are about −20 °C. Based on the analysis of the empirical distribution function of temperature at the mountain meteorological station, Kazbegi-visokogornaya, the absolute minimum temperature on the plateau is about −40 °C. In April–May and in September–October, in rare cases, short-lived thawing conditions may occur when the weather is governed by the strong powerful tropical air advection. In the summer months, the daytime temperature may reach up to +5 °C. However, the mean long-term summer temperature values are below zero. During the field work in 2015, direct meteorological observations on the Kazbek plateau were carried out: air temperature and humidity, wind speed and direction, turbulent fluxes of heat and moisture, and radiation balance were monitored for 3 days.

The precipitation regime is characterized by large spatial variability. Total annual precipitation decreases from the western to the eastern Caucasus by a factor of 10 (Volodicheva 2002). The large distance from the Black Sea and that from the Mediterranean Sea coupled with the mountainous terrain are the main factors driving that difference.

The seasonal precipitation distribution is characterized by a summer maximum (May–August). The summer maximum of precipitation though is less pronounced at higher elevations (Fig. 2). The amount of winter precipitation at the Kazbegi station is substantially higher than on the plains. This is due to the “barrier” effect of the Caucasus Mountains: the Main and the Side Caucasus ridges intercept most of the moisture that is advected frequently

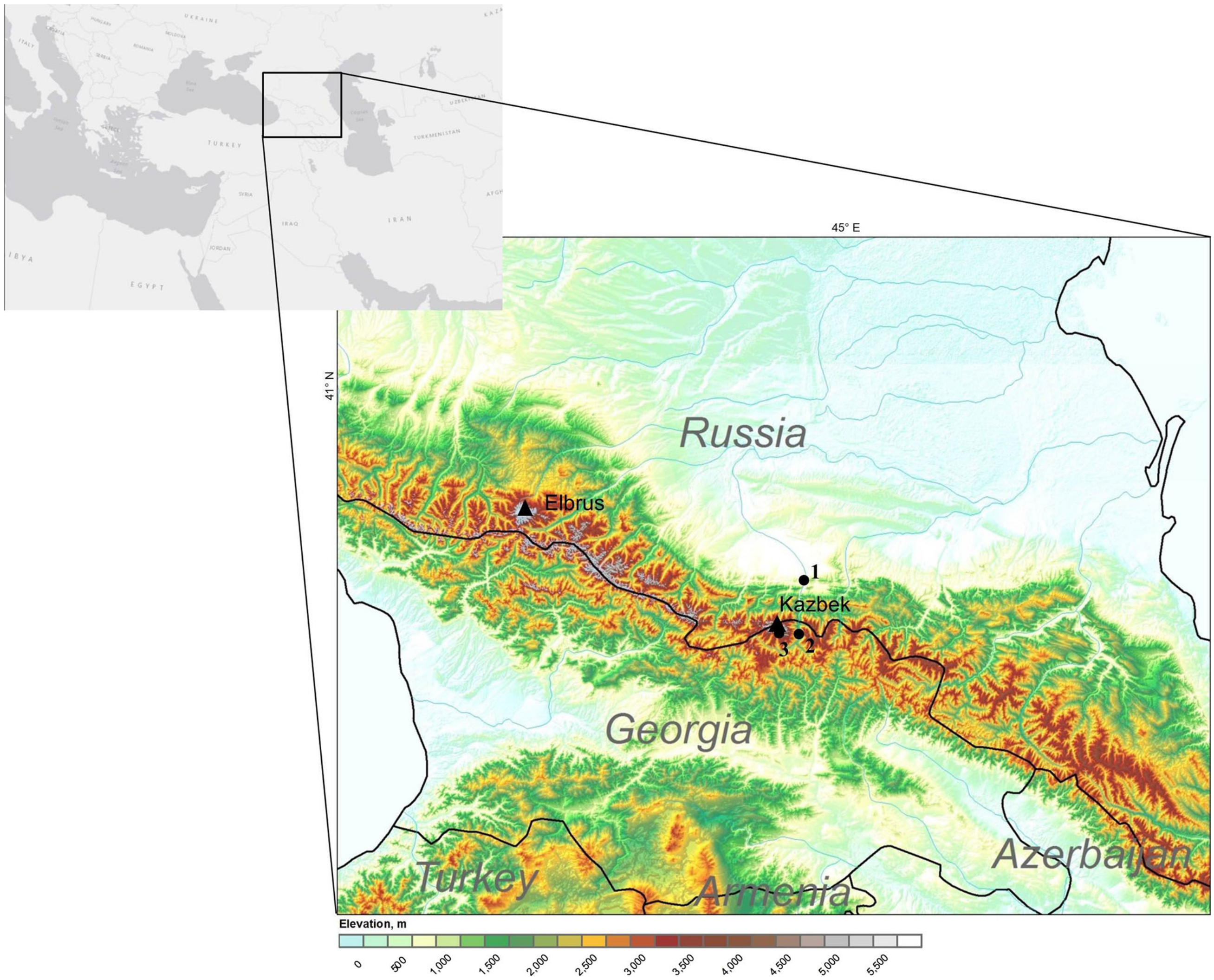

Fig. 1 Map showing Caucasus Mountains, Mt. Kazbek, Mt. Elbrus. Location of meteorological stations is shown by *black circles*: *1* Vladikavkaz, *2* Kazbegi, *3* Kazbegi-visokogornaya

Table 1 Characteristics of the thermal regime of the Central Caucasus from direct measurements

Meteorological station	Elevation (m)	Surface air temperature (°C) for the period from 1965 until 1991					
		Winter	Spring	Summer	Fall	Mean annual	Temperature range
Nalchik	450	−1.7	8.7	20.5	9.7	9.3	22.2
Vladikavkaz	750	−2.2	8.9	19.3	9.1	8.7	21.5
Kazbegi	1850	−4.4	4.0	13.4	6.2	4.8	17.8
Kazbegi-visokogornaya	3500	−13.2	−7.6	2.2	−3.5	−5.5	15.4
Kazbek Plateau (estimated values)	4500	−19.9	−10.4	−4.1	−11.9	−11.6	15.5

from the Black Sea and the Mediterranean Sea. In the summer months, the differences are less pronounced because there is a high repeatability of orographic occlusion, since an important role is played by the mesoscale factors, i.e., orographic occlusion and orographic convection.

Ice thickness measurements

A monopulse ground-penetrating radar (GPR) with the central frequency of 20 MHz was used to determine ice thickness and to evaluate characteristics of the internal glacier structure. The instrument, denoted as VIRL-6,

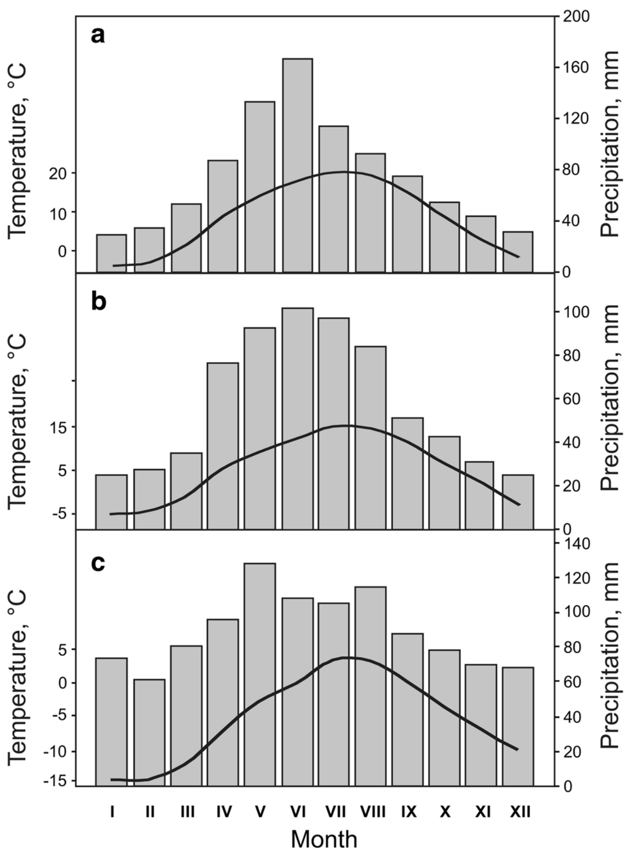

Fig. 2 Directly observed seasonal change in temperature and precipitation at meteorological stations "Vladikavkaz" (**a**), "Kazbegi" (**b**), and "Kazbegi-visokogornaya" (**c**)

has been described in detail in Vasilenko et al. (2011). An optical cable is employed in the instrument to transmit the signal. It is important to note that this instrument is characterized by a high signal-to-noise ratio (SNR), a high transmitter power and a long recording time window. The instrument is light-weight and could be carried in a backpack by operators in hard to access mountainous regions. The accuracy of ice thickness measurements was estimated by data comparison in the profile intersection areas and amounted to $\pm$ 3%. The combined length of profiles of ice thickness measurements was 7.6 km (Fig. 3). The data treatment was performed using the RadexPro software (e.g., Lavrentiev et al. 2010).

The glacier surface topography survey has been conducted using a double-frequency differential GPS receiver (DGPS) Topcon GB 500. The map of ice thickness and bedrock relief topography on the Kazbek plateau was completed by interpolation between the obtained bedrock reflections using the ANUDEM algorithm in ArcGIS 10.2 software (Fig. 3.).

$\delta^{18}O$ and δD measurements

Snow and ice samples were collected in vials with a 10-cm resolution for $\delta^{18}O$ and δD measurements. Isotopic measurements were performed using a laser analyzer Picarro L2120-i at the Climate and Environmental Research Laboratory, Arctic and Antarctic Research Institute (St. Petersburg, Russia). The instrument is regularly calibrated against the International Atomic Energy Agency standards (SMOW, GISP и SLAP; detailed information about the standards is available at www.iaea.org). For the measurements of samples, the home standard with the isotopic values close to those of the samples was used. Measurements of each sample were performed once; however, several randomly chosen samples were measured twice to test precision. The precision of the $\delta^{18}O$ measurements was ± 0.1‰, and the precision of δD was ± 1.0‰.

Particle concentration measurements

The samples were analyzed for total concentration and size distribution of microparticles using the Multisizer™ 3 Coulter Counter® instrument at Laboratoire de Glaciologie et Géophysique de l'Environnement (France). Sample preparation and analyses were performed in a class-100 clean room to minimize possible contamination. Concentrations were measured in the range from 1 to 30 μm on 300 channels.

Scanning electron microscope and X-ray diffraction analyses

Microstructural studies of the dust samples were performed using a scanning electron microscope (SEM) LEO 1450VP (Zeiss) at the Moscow State University. Powdered samples were fixed on a support table with an aid of a carbon conductive tape. Pouring of samples was carried out so that the individual particles would not overlap. Then, samples were coated with 10–20 nm of gold in a sputtering system to prevent the effect of sample charging during the SEM study.

Investigation of mineral composition of dust samples was done by X-ray diffraction using an Ultima-IV X-ray diffractometer (Rigaku) at the Moscow State University. XRD patterns were collected from non-oriented samples of dust powder. Measurement conditions were as follows: Cu-K_a radiation, D/Tex-Ultra 1D-detector, scan range 3.6–65° 2θ, scan speed 5°/min, step—0.02° 2θ. The diagnostics of the mineral composition was performed by comparing the experimental and reference spectra from the database PDF-2 using the software package Jade 6.5 (MDI) employing

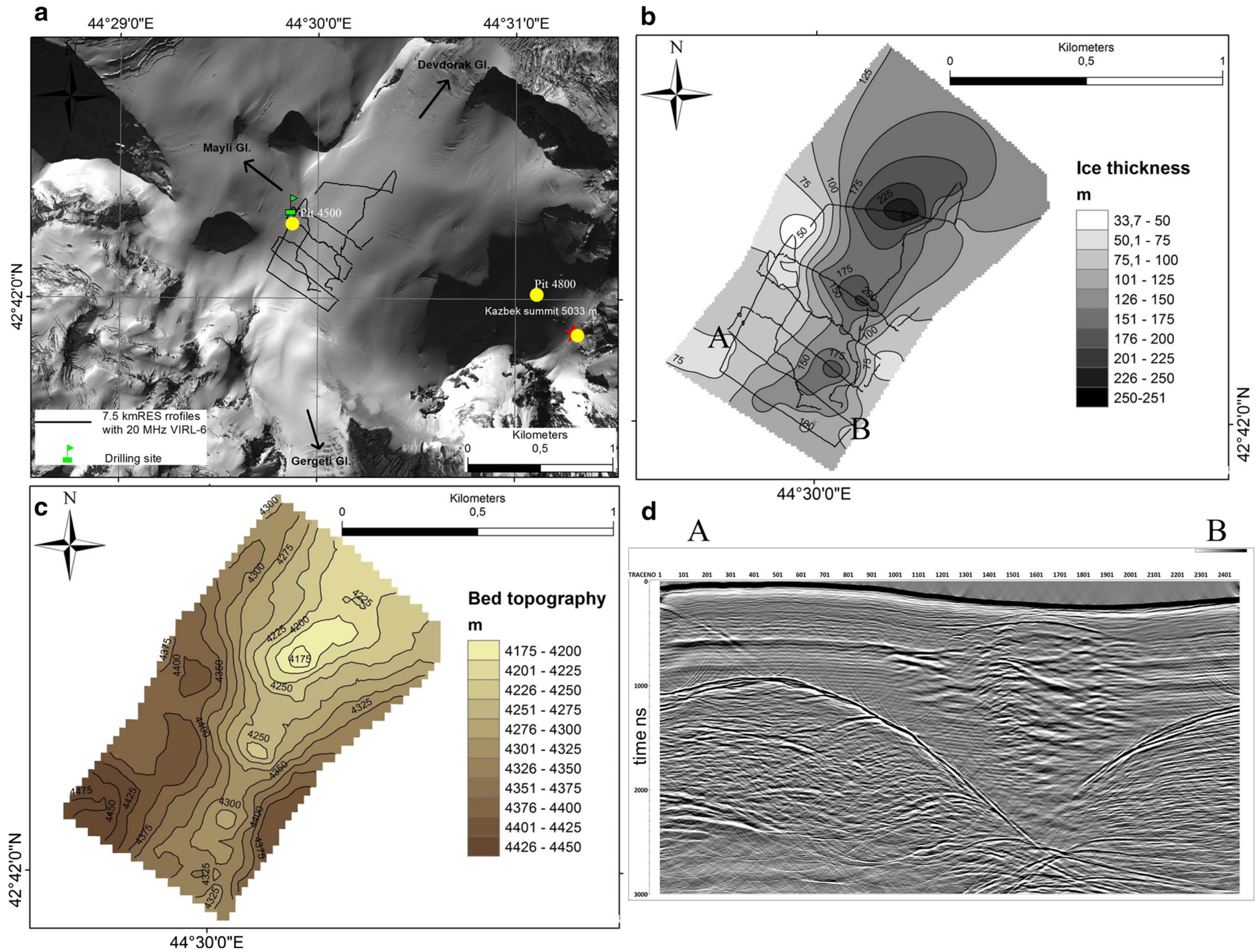

Fig. 3 Location of the shallow drilling site on the Kazbek plateau (4500 m) and GPR survey profiles obtained during the 2014 field season are shown (**a**). Glacier thickness and the relief of the basement are shown in panels (**b**, **c**). Internal structure of the glacier, most importantly layers being parallel, is apparent from the GPR image (**d**)

specialized literature (Dritz and Kossovskaya 1990; Moore and Reynolds 1997). Quantitative analysis was carried out using the full-profile fitting by the Rietveld method (Bish and Post 1993) with BGMN software (www.bgmn.de). The precision of calculations of quantitative content by the Rietveld method is generally estimated at 2–3%. The error in determination consists of calculating errors for each phase and is given in percent by weight. At the same time, the determination error for the individual phases may vary and can range from 0.5 to 3%.

Results

Glacier survey

The bedrock topography reveals a depression extending from southwest to northeast and bordered from the east by the massif of Mt. Kazbek. The average ice thickness along the central axis of this depression is 170 m, and it decreases toward sides to 50–70 m. The maximum measured ice thickness amounted to 250 m in the northwestern part of the plateau. The outflow of ice into this area occurs from three directions: from the summit of Mt. Kazbek, from southwest along the main fold of the depression, and from the ridge limiting the plateau from the west. Therefore, this point would be a poor selection for an ice core drilling site because of the complexity of the ice flow. Given the bedrock relief topography, the suitable location for the ice core drilling is located near the ice divide of the Gergeti glacier from the southwestern part of the plateau (Fig. 3). The average ice thickness here ranges from 150 to 160 meters. At the same time, the available data do not allow us to completely eliminate the inflow of ice from the summit of Mt. Kazbek. Therefore, further ice flow modeling is needed to confirm the suitability of a chosen site.

Stratigraphy

The analyses performed on the Kazbek shallow ice core of 2014 showed that the core captures the time interval from 2009 (Fig. 4). At the depth of 3.8 m, the presence of low density firn did not allow collecting the sample, which caused a void in our record. While the 2015 core extended the record, it again failed to capture the firn at the depth of the void due to the freezing-in of the corer at that depth (Fig. 5). The dating was performed using the ice core stratigraphy, the isotopic composition (using characteristic winter minima in $\delta^{18}O$), as well as using total dust concentration. Dating of the Kazbek ice core allowed calculating the average (over 5 years) snow accumulation rate of 1800 mm (water equivalent) per year.

In the summertime, the top layer of snow is subject to melting which causes formation of numerous melt layers. The maximum thickness of the melt layers in the summer layers was 6.5 cm. Numerous highly visible dust layers were observed. Density measurements allowed determination of the total water amount in the ice column.

Isotopic composition

Summer melting at this site does not seem to sufficiently affect the seasonal isotopic signal (Fig. 4). Without further investigation, it cannot be ruled out that some smoothing of the isotopic profile may occur as a result of melting and possible percolation into the underlying layers. The mean value of $\delta^{18}O$ is -12‰ which was considered as a threshold between warm and cold seasons or summer and winter correspondingly. The typical values of $\delta^{18}O$ in summer horizons are in the range from -7 to -5‰, whereas for winter horizons the $\delta^{18}O$ values are below -15‰. The low $\delta^{18}O$ value of winter 2012–2013 that stands out has been caused by particularly cold conditions. Despite the elevation difference of more than 500 m, records from three snow pits show a similar isotopic composition (Fig. 5a). The deuterium excess values ($d\text{-}excess = \delta D - 8 \times \delta^{18}O$) are higher than one would expect from the global meteoric water line and vary from 13 to 23‰ with the average value of 18‰. Deuterium excess does not correlate with the $\delta^{18}O$ values and shows no seasonal variations. High values of *d-excess* can be explained by the distillation during air mass pathway or by high *d-excess* values of the moisture source. Several snow and firn pits at the Kazbek plateau and on the summit were compared. All the cores have the same $\delta^{18}O$ and *d-excess* values during all the overlapping periods. The $\delta^{18}O$ records obtained at Elbrus and at Kazbek were compared and the following results were obtained. In the summer period, the isotopic composition of the both cores is very close, the difference is 1‰ at maximum, while in winter the difference is about 5–6‰. The extremely cold winter of 2012–2013 is an exception: the $\delta^{18}O$ values of the two cores are equal.

Microparticle content and characteristics

Seventeen horizons with exceptionally high concentration of microparticles in the Kazbek ice core were identified. The analyses allowed estimating, for the first time, the total supply of mineral substances on the glacier. The main morphological characteristics of the particles in the Kazbek

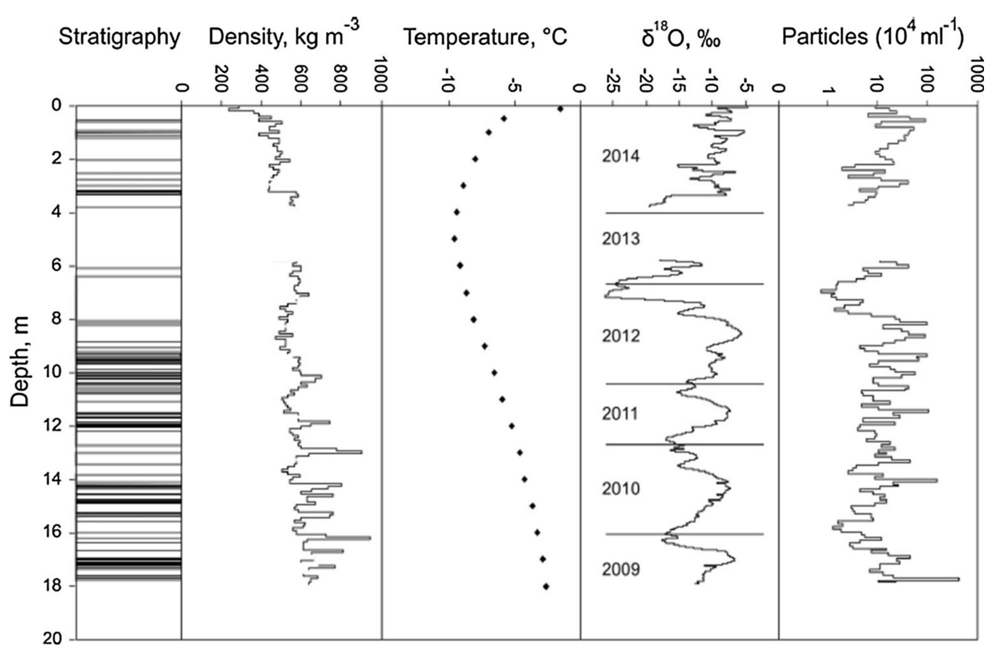

Fig. 4 Ice core stratigraphy (*black*- melt features, *gray*- dust layers), physical characteristics, oxygen isotopes, and particle concentration

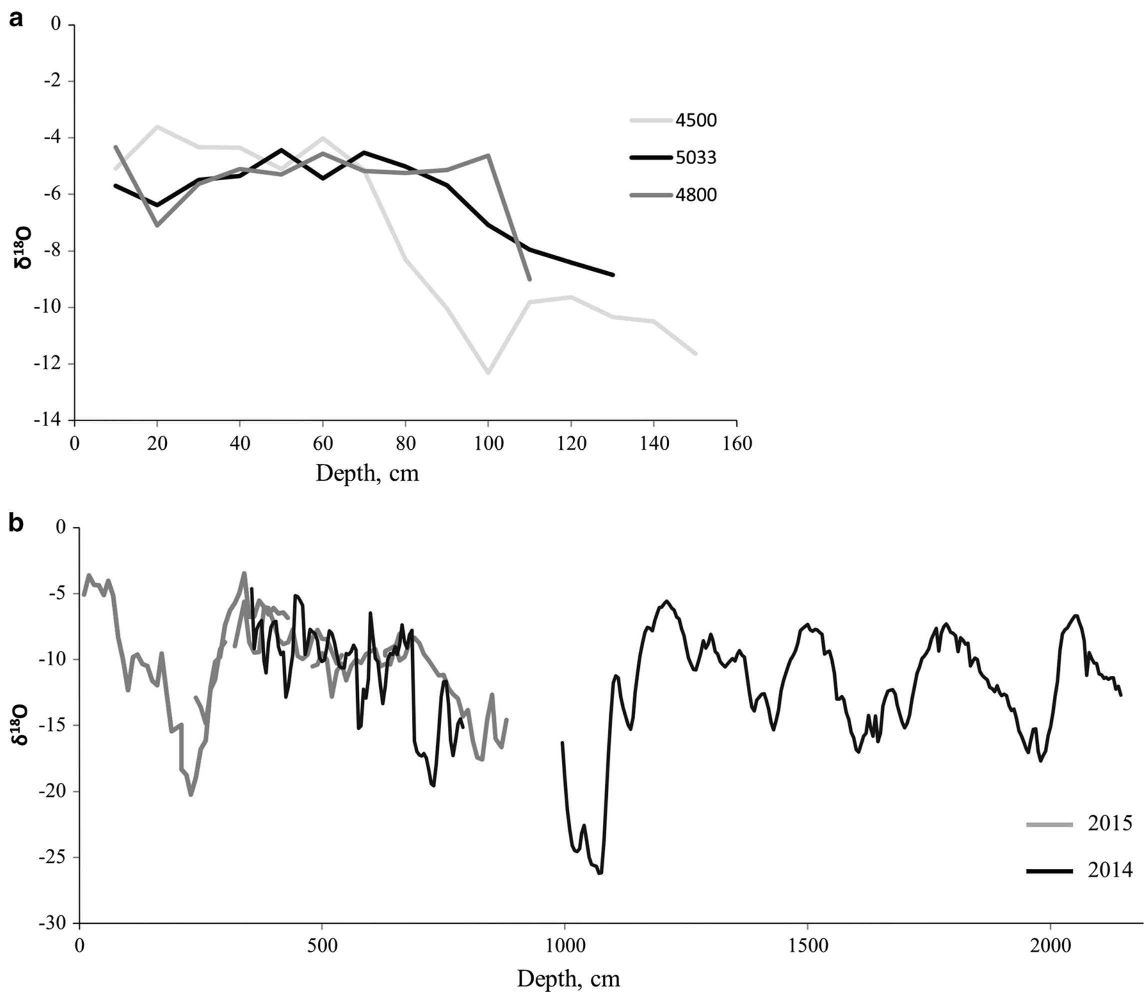

Fig. 5 Oxygen isotope data for the 2014 and the 2015 sampling seasons. Data from the snow pit samples from different elevations are shown (**a**)

ice core were determined. The average concentration of microparticles in the Kazbek ice core is 2×10^5 particles/ml with the maximum values reaching 4.5×10^6 particles/ml for some extreme events. The concentration of microparticles is 6.9 mg/l on average, the highest value being 140 mg/l. The interannual variability in the supply of solid matter to the surface of the Kazbek glacier was determined. The total dust flux was estimated for three complete years 2010–2013 and was on average 1.3 mg/cm^2 a^{-1} (Table 2).

The morphology and mineralogy of particles was determined, which allowed separating samples into two groups. Rough clastic unsorted particles were a typical characteristic of samples reflecting predominantly local origin. Feldspars and other minerals of magmatic rocks are dominant in mineral composition, while clay minerals are absent (Table 3; Fig. 6). For the second group of dust samples, there is a significant proportion of dust carried over large distances, presumably from the deserts of Middle East and Sahara (Kutuzov et al. 2013). Here in the mineral composition dominant are quartz, calcite, kaolinite, dolomite, smectite, and illite. This material is sorted, for some particles sharp angles are practically absent (Table 3; Fig. 6). Such division was confirmed by the analysis of distribution of particles by sizes (Fig. 7). For the remote-origin samples, lower values for the median of the mass (volume) distribution of particles (4–5 μm) are observed. For the local mineral particles, the median value was around 7 μm. The log-normal distribution in the latter case was distorted due to the presence of a large number of particles having sizes greater than 10–15 μm.

Discussion

Glacier structure

The GPR survey conducted on the Kazbek plateau showed that the maximum depth of the glacier is 250 m. There were no systematic studies of glaciers employing radio

Table 2 Estimation of the total annual dust supply to the Kazbek plateau from the ice core for the period 2010–2012

Ice core site	Elevation (m a.s.l.)	Year	Accumulation (mm w. e.)	Dust mass concentration (mg l^{-1})	Dust flux (mg/cm^2 a^{-1})	Reference
Kazbek plateau	4500	2012	1992	7.60	1.51	This study
		2011	991	5.60	0.55	
		2010	2381	7.85	1.87	
Elbrus western plateau	5115	2012	1500	1.23	0.19	Mikhalenko et al. (2015), Kutuzov et al. (2017)
		2011	1500	0.66	5.60	
		2010	2620	0.99	7.85	

The data for Elbrus western plateau (Kutuzov et al. 2017) are provided for direct comparison

Table 3 Average mineral composition of dust samples of local and long-distance origin (in %)

Dust origin	Quartz	Plagioclase	Calcite	Dolomite	Rhodochrosite	Kaolinite	illite + I/S[a]	Smectite
Local	8.8	69.3	0	0	2.3	2.6	17.0	0
Long-distance	7.2	8.1	4.6	2.0	0.2	4.1	61.4	12.5

[a] I/S – illite–smectite ($I \gg S$) mixed layered minerals

echo sounding on Kazbek previously. Such studies are of great practical importance, since they can accurately determine the amount of ice that could potentially be destabilized if bedrock heating occurs due to invigoration of volcanic activity. The fumarole activity on Mt. Kazbek is widespread, and it is well known that some glaciers of Kazbek are characterized by surge behavior, which may be related to volcanic bedrock heating. Importantly, the results of deep glacier drilling provide information about the temperature distribution inside the glacier and allow calculation of the heat flux. As shown in the work of Likhodeev and Mikhalenko (2012), these data can be used to calculate the position and temperature of the magma chamber.

The GPR profiles depict a fairly large thickness of ice on the plateau. The analysis of radar recordings allowed identification of the glacier zones where the ice flow does not disturb the parallel layering in the glacier. In general, the internal reflectors may be considered as isochronous surfaces. The observed structure supports the assumption of the preservation of annual layers inside the glacier. (Fig. 3d). Based on the obtained data on the ice thickness and the average snow accumulation rate on the plateau, the age of the ice at the bedrock was estimated using the Nye model (Nye 1963). The resulting age at the depth of 150 m is about 300 years.

Factors influencing the isotopic signal

Regarding the isotopic signal, it should be mentioned that the precipitation isotopic composition at the GNIP (Global Network of Isotopes in Precipitation) stations (Tbilisi, Batumi, Bakuriani, see Mikhalenko et al. 2015 for details), which are situated much lower that the drilling sites, is almost the same as those on the glaciers in summer season. In winter, the prominent gradient of the isotopic composition is observed. One possible explanation is the uniform moisture source for precipitation in the summer for the whole region and different sources for low and high elevations in winter. Another possible explanation is the isotopic enrichment of winter layers during summer melting (Koerner 1997).

Total flux of mineral substances

As a result of analyzing snow and firn samples on the microparticle content, the total flux of mineral substances on the glacier from the atmosphere can be estimated for the first time. The main morphological characteristics of the particles extracted from the ice were determined. The calculated average dust flux for over three years at Kazbek was of 1.3 mg/cm^2 a^{-1}, which is about 7 times greater than the dust flux registered at the Mt. Elbrus western plateau (Kutuzov et al. 2017) over the same time interval (Table 2) due to a great difference in dust mass concentrations on the two glaciers. Apparently, the main factors are the elevation, the presence of a large number of open rock and moraine areas in the vicinity of the Kazbek plateau, and the geographical position of Kazbek (~190 km east of Mount Elbrus) resulting in differences in air masses. The main pathways of the air masses from the Middle

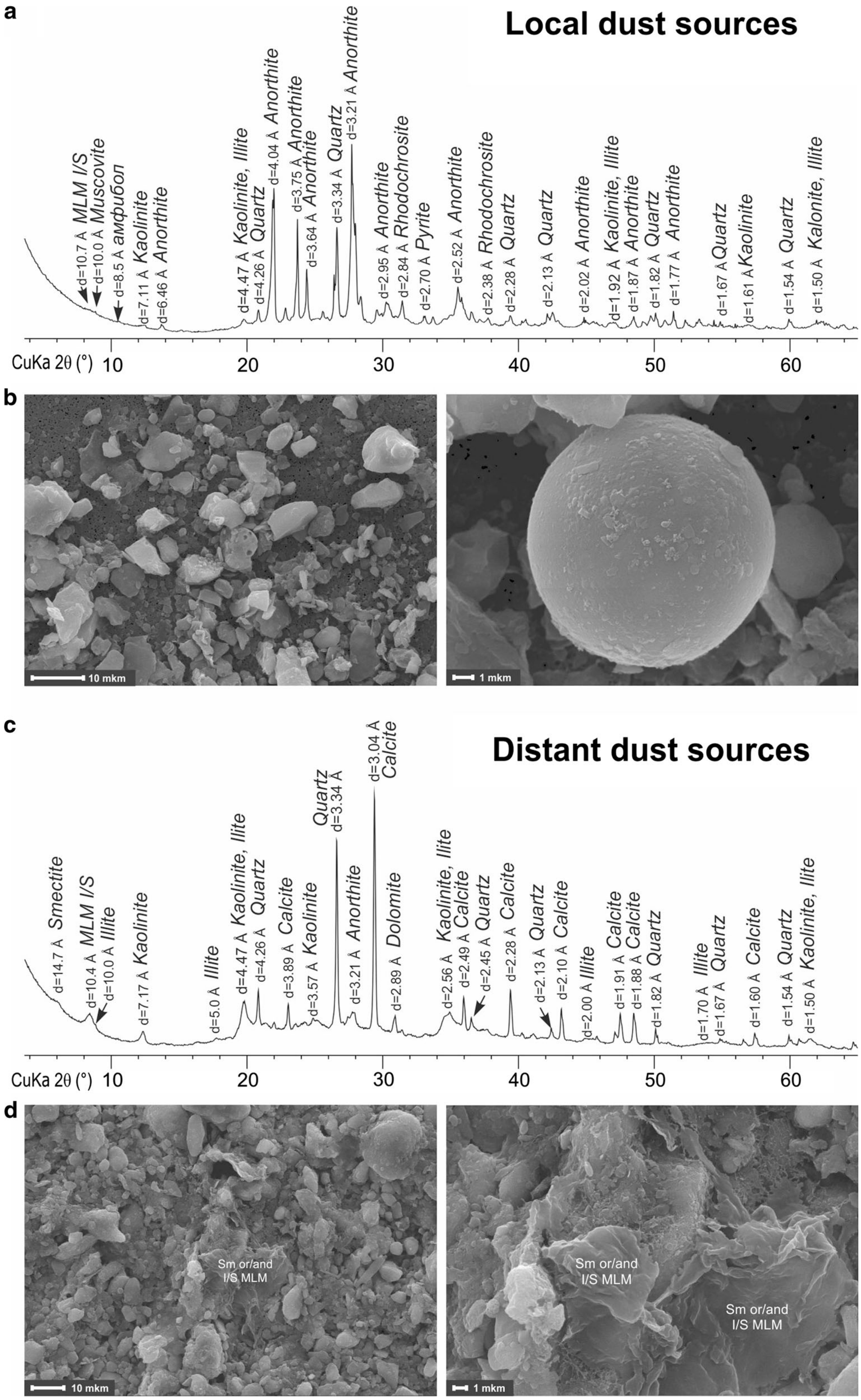

Fig. 6 Mineral composition by the XRD and microstructure by SEM of dust particles: **a**, **b** predominantly local dust sources particles. **c**, **d** Predominantly distant dust sources particles in the ice of Kazbek plateau glacier. **a**, **c** Powder X-ray diffraction patterns. **b**, **d** Scan electron microscopy images

East pass through the eastern sector of the Caucasus. The electron microscope and X-ray diffraction analyses of the particles that were conducted showed the presence of non-local dust horizons in the Kazbek ice core that likely originated in Middle Eastern deserts and the Sahara desert.

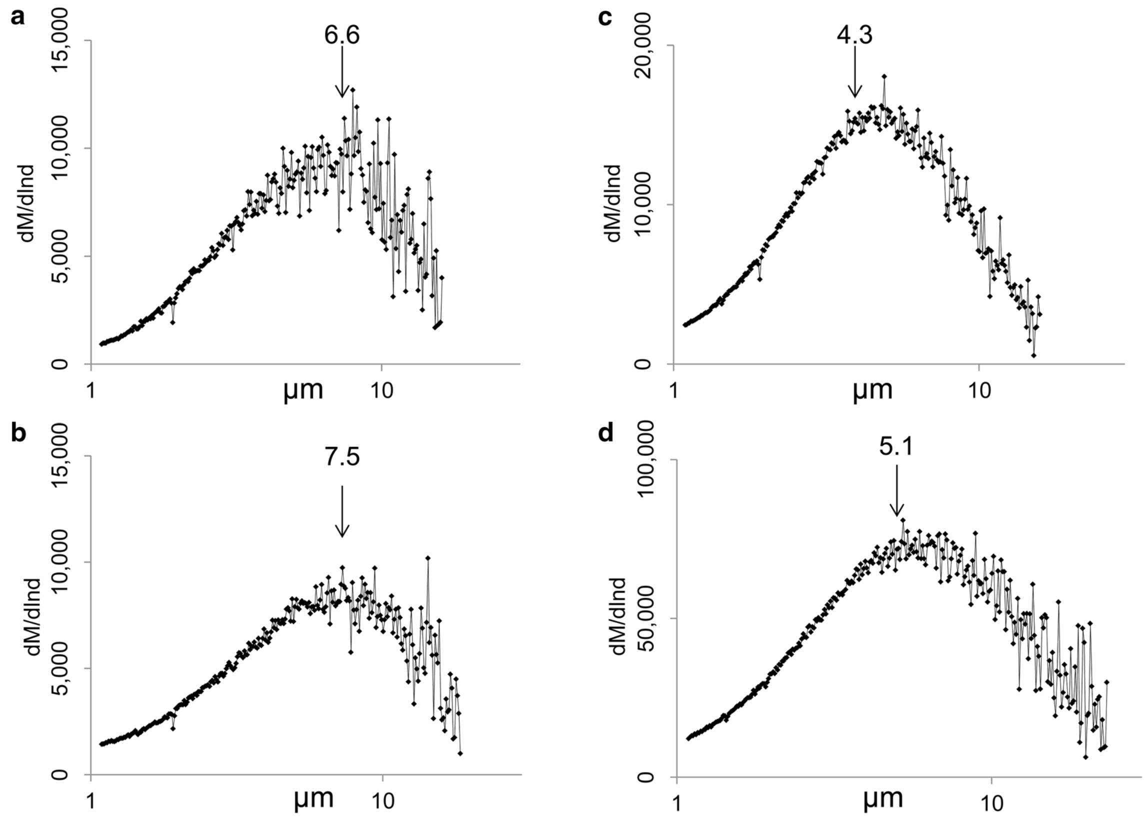

Fig. 7 Dust particle size distribution for a local (**a**, **b**) and distant dust samples (**c**, **d**). **a**, **c** Elbrus. **b**, **d** Kazbek

Comparison with Mt. Elbrus

The suitability of using deep ice cores from the Caucasus for paleoclimatic reconstructions has been demonstrated by the Elbrus ice core (Mikhalenko et al. 2015). The drilling site elevation on Mt. Kazbek (4500 m) is significantly lower than the drilling site elevation on Mt. Elbrus (5115 m). Therefore, the ice temperature is substantially higher at Mt. Kazbek. The temperature at a depth of 10 m at the drilling site on Mt. Elbrus amounted to −17 °C, whereas the glacier temperature at the same depth on Mt. Kazbek is ten degrees higher (−7 °C). The depth of 10 m approximately corresponds to the border, below which the effect of seasonal changes in surface temperature vanishes. The temperature at this depth is a good approximation of the mean annual temperature. Using the relationship:

$$T_{10} = 1.2T_a + 6.7, \qquad (1)$$

where T_{10} is temperature at a depth of 10 m and T_a is the mean annual surface air temperature (Zagorodnov et al. 2006) the mean annual air temperature of −11.4 °C was estimated. This temperature is offset by only 0.2 °C from the temperature calculated using a lapse rate and the direct observations from the meteorological stations at lower elevations.

It is important to note that, unlike on Mt. Elbrus, the air temperatures at the Kazbek plateau occasionally can reach values of up to +5 °C during the summer. The maximum height on Kazbek is 5033 m. Therefore, colder glaciers in principle exist there; however, the analysis of the existing ice cover shows that no plateaus are available above 4500 m.

Comparison with the Alps

In this section, the Kazbek plateau drilling site is compared with various sites in the Alps, where extensive ice core work has been carried out over a few decades (see Table 4). It is widely recognized that the ice core studies in the Alps made a significant contribution to the understanding climatic and atmospheric processes. As can be seen from Table 4, conditions on the Kazbek plateau are comparable to the deep ice core drilling sites elsewhere in terms of air temperature, ice thickness, etc. As a result, it

Table 4 Characteristics of the selected high-altitude ice coring sites in Europe (the Alps) in comparison with the new sites in the Caucasus

Mountain range	Massif	Specific area	Drilling site characteristics				
			Elevation (m a.s.l.)	Approximate firn T at 10 m (°C)	Mean annual accumulation rate (m w.e.)	Depth (m)	Selected references
Alps	Monte Rosa	Colle Gnifetti glacier (45°55′N, 7°52′ E)	4455	−14	0.2–1.1	130	Thevenon et al. (2009), Luthi and Funk (2001)
	Mont Blanc	Col du Dome glacier (45°50′N,6°50′E)	4250	− 7	0.5–2.4	150	Preunkert et al. (2000), Maupetit et al. (1995), Vincent et al. (2007)
	Area between mountains Gross Fiescherhorn, Hinter Fiescherhorn, and Ochs	Fiescherhorn glacier (46°33′N, 8°04′E)	3900	−5	1.4	150	Jenk et al. (2006), Schwikowski et al. (1999)
	Ortles	Alto dell'Ortles glacier (46°30′N, 10°32′E)	3830	−1	1.2	75	Gabrielli et al. (2010)
Caucasus	Elbrus	Western plateau (43°20′N, 42°25′E)	5115	−17	1.4	255	Mikhalenko et al. (2015)
	Kazbek	Kazbek plateau (42°42′N, 44°30′E)	4500	−7	1.8	250	This study

can be expected that at a comparable quality of environmental signal recorded in the Kazbek ice cores will cover a shorter period of time with a high seasonal resolution.

Of particular interest for evaluating the maximum glacier temperature at which the paleoenvironmental record is still usable, is the recently drilled ice core on Mt. Ortles in the Alps, Italy (Gabrielli et al. 2010). In spite of the relatively low elevation of 3905 m a.s.l. and a corresponding high temperature of the glacier, it was possible to extract paleorecords of reasonable quality (Gabrielli et al. 2012). Similarly to the Mt. Ortles glaciological paleoarchive, the Mt. Kazbek archive is in danger of being lost if infiltration increases during warming in the following years.

Conclusions

As a result of this work, it was determined that the thickness of the ice on the Kazbek plateau near ice divide is 160 m, with the maximum thickness of the glacier reaching 250 meters. The internal structure of the ice indicates that the glacier is composed of parallel and homogeneously distributed layers. These data, complemented by the bedrock topography data, allow identification of the most suitable location for future deep core drilling efforts. The borehole measurements performed in this study indicated that the temperature of the active layer (10 m) is −7 °C, rising to −2.7 °C at a depth of 18 m. The first Kazbek shallow ice core captures the time interval from 2009 to 2015. Ice core stratigraphy shows presence of melt features in summer layers (up to 6.5 cm) and pronounced dust horizons. Isotopic record shows a distinct seasonal cycle with $\delta^{18}O$ varying from around −5‰ in the summer layers to around −20‰ in winter layers of the ice core. The average snow accumulation rate over the period covered by the ice core is 1800 mm w.e. The record is characterized by an extremely high resolution, which allows seasonal changes to be studied.

Seventeen horizons in the ice with an extremely high dust content were observed. The high-altitude ice cores from the Caucasus can be regarded as the long-distance geochemical archives of the processes in the arid areas of the Middle East that serve as major glacier dust sources. The first estimate is made for total amount of dust arriving annually on the Kazbek plateau, which proved to be 7 times greater than that for the Mt. Elbrus deep drilling site. The mineralogical analysis applied in our work shows that local and remote sources of dust can be distinguished and their contributions can be quantified. In order to identify the sources from which the transfer takes place and for the analysis of the temporal trends, a detailed provenance analysis of both Elbrus and Kazbek cores is needed in continuation of previous work (Shahgedanova et al. 2013, Kutuzov et al. 2013, 2014).

While our calculation of the mean annual temperature on the Kazbek plateau based on the available meteorological data yielded a value of −11 °C, it is important to note that the maximum summer temperature can reach +5 °C. During anomalously warm years, the possibility of infiltration of melt water beyond the layer deposited during that year into the previous annual horizon cannot be ruled out. Despite these limitations, it is safe to conclude that the Kazbek plateau provides a valuable opportunity for extracting paleoenvironmental data characterized by large-scale implications.

Preliminary estimates show that the 150 m ice core from the Kazbek plateau may contain high-resolution data over the time interval of around 300 years. The Kazbek ice core data will complement the existing global database on climate changes of the temperate latitudes. Changing climate puts glaciers of tropical and temperate latitudes at risk. The records from these glaciers may be permanently lost as the interior temperatures of the glaciers increase and the amount of meltwater amount increases. The glaciers of Mt. Kazbek are situated at critically low altitudes and are among the ones that should be sampled most urgently.

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